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SAR interference suppression

Field of the invention

The present invention relates to the field of synthetic aperture radar, SAR. More particularly, the present invention relates to VHF SAR.

Background

Airborne Low Frequency Synthetic Aperture Radar operating in the VHF and UHF bands is becoming an important emerging technology for wide area surveillance and target detection in foliage. To obtain sufficient resolution, viz. a few meters or less, the radar-operating band must extend over several tens of Megahertz, i.e. radar reception must be wide band and occur across frequency bands allocated for radio and TV broadcasting.

A VHF synthetic aperture radar system denoted CARABAS™ (Coherent All Radio Band Sensing) SAR system has been described in US-4965582 and US4866446. An ultra wide band coherent radar system has been disclosed US-6072420.

High speed computing enables the possibility of applying virtually any algorithm as a filter function on streaming data. This fact opens the route to obtain signal-processing functions, which would be too complex to be realised by hardwired filters. Active noise suppression is one such application in which ambient noise is recorded and a mirror signals is processed, amplified generated by means of a loudspeaker. The mirror signal is generated in a timely and accurate fashion so as to cancel the noise at a given point (at the object to be protected from the noise). This principle has been used in cars using existing car audio equipment, in headphones and in mobile telephones. However, it has been considered unfeasible to use interference cancellation for radar applications.

As for the application of interference rejection techniques in low frequency SAR, two types of filtering techniques can be envisaged:
- narrow-band notching techniques that can be analogue pre–reception, or
- digital post-reception carrier cancellation techniques.

The first category is of little relevance since parts of the radar range spectrum is blocked, which is unacceptable for radar operation. Moreover, range side-lobes are produced which leads to a degradation of radar performance.

For the second category only the carrier wave is removed, which is deemed insufficient.

Summary of the invention

It is a first object of the invention to set forth a radar system in which VHF and UHF band communication signals, e.g. radio and TV signals, are actively suppressed, so as to enable the radar system be used in areas where such signals are prevalent and to enable co-existence with such communication systems.

It is a second object of the present invention to set forth a filter and a method, which facilitate the use of the VHF and UHF band for the purpose of receiving radar signals with a frequency content extending across radio and TV bands.

From the viewpoint of broadband signal reception in the VHF/UHF band, two different external noise components are of concern:
- a random noise component at an elevated noise temperature (perhaps 30 dB above thermal noise for VHF); and
- the modulated interference from radio and TV transmitters.

The effect of the modulated interference on the SAR image is similar to the effect of the random noise component. The degree to which interference will disrupt the SAR image can thus be measured by its power across the reception bandwidth and the integration time of the SAR process.

The power from a TV transmitter entering into an isotropic antenna at a typical distance of 100 km from the transmitter will be of the order 40 dB stronger than the power of the stochastic noise component across the same bandwidth (5 MHz). It is thus 30 dB stronger than the power over a typical operational bandwidth of the SAR (50 MHz).

It is thereby clear that just to compete with stochastic noise calls for a 30 dB increase of transmit power compared to a situation of purely thermal noise. To defeat the interference from radio and TV would require a further 30 dB increase of transmit power. Even if such an increase would be technically feasible it would be unacceptable since it would disrupt the broadcast signal, as mentioned.

In order to make the radar signal cause a minimum of disruption to broadcasting, the transmitted power across the radio and TV bands must be kept low, balanced by a higher power outside these bands. The received radar signal spectrum must have uniform amplitude in the SAR image processing, or the resulting radar image will exhibit side-lobes, degrading the ability of the radar to detect targets. To obtain a uniform spectrum, a low transmitted radar signal amplitude across the interfering bands can be compensated for by a frequency dependent gain. This requires some efficient means of suppressing the influence of the broadcast signal, or the weighting process will inject intolerable levels of interference and noise in the SAR image. The filter solution proposed is intended for this purpose of interference cancellation.

The filtering according to the invention accomplishes a reduction of interference energy by the order of 40 dB. It is thereby on parity with the stochastic noise component, which by its nature cannot be removed from the received signal. Consequently, the degrading effect of radio interference on SAR imagery might be substantially removed

The crucial difference between the modulated and the random noise component is that the former contains intrinsic dependencies making its information bandwidth smaller – perhaps even much smaller – than its nominal bandwidth. The inference suppression filter according to the invention exploits the dependencies in order to remove as much as possible of the interference component from the incoming radar signal, thereby also reducing the energy content of the interference.

A filter scheme for broadcast interference cancellation that is computationally efficient and numerically robust is accomplished by the present invention.

According to one aspect of the invention, interference removal is achieved by using the internal dependencies of the message in order to predict the message beyond some moment of time up to which the message is known. The interference component in the received radar signal can thus be identified and subtracted or otherwise removed.

Brief description of the drawings

Fig. 1a shows a first embodiment of a Doppler filtering and cancellation VHF SAR system,

Fig. 1b shows a second embodiment of a Doppler filtering and cancellation VHF SAR system, and

Fig. 2 shows a filter for interference prediction according to a third embodiment of the invention.

Detailed description of preferred embodiments of the invention

Two basic methods of interference suppression are proposed. They will be referred to as interference Doppler filtering and interference cancellation; the meaning of these terms in the present context will be explained in the following. According to one embodiment of the invention, the two methods are combined, in a serial arrangement.

Interference Doppler Filtering

In Figure 1a and 1b, two alternative interference Doppler filtering and cancellation embodiments for a VHF SAR system according to the invention are shown.

The interference Doppler filtering according to the invention is based on a prediction of the phase of the interfering signal over subsequent radar reception intervals. Adopting the estimated phase for transmission across the interfering bands, phase variations of the interference signal will cancel upon radar pulse compression (convolution with the transmit signal), cf. Figure 1a and 1b. Hence interference will appear concentrated to a DC component in the received radar Doppler spectrum and can be blocked by thresholding in 2-dimensions rather than one.

The radar system comprises an aerial 11, an input / output switch 10, a transmit amplifier 1, a receiving amplifier 2, a demodulator 3, a storing unit 4, a prediction unit 5, a

phase unit 6, a signal generating unit 9, and a 2-dimensional filter 8. Moreover a subtraction unit 12 and a phase conjugate multiplier 7 are provided.

In a first embodiment shown in fig. 1a), there is moreover provided a first input switch 13, an attenuator 14 and a second input switch 15. The receiver captures radio interference frames, a sequence of which is exploited to predict the interference component of the combined signal of interference and radar response. The predictions are utilised to 1) subtract the interference component from the combined signal and 2) make the combined signal coherent from pulse to pulse. The latter allows 2-dimensional filtering in the range and Doppler domain after pulse compression. Subtraction can be carried out before receiver front end, thus reducing the demand on receiver dynamic range by either subtracting interference or attenuating the signal just to receive the interference component.

In a second embodiment shown in fig. 1b), the same combination of subtraction and 2-dimensional filtering, as in fig. 1a) is provided. The difference from the first scheme is that the combined radar and interference signal is utilised to separate interference and radar data. The possibility of this scheme relies on the low pass filtering of the predicted interference signal (cf. Figure 2). Because of this, radar data, which are added to interference and subsequently subtracted, are first filtered to below a few Hertz of Doppler bandwidth, viz. to the band which anyway will be notched in the subsequent 2-dimensional filtering.

The advantage of scheme of fig. 1b) over fig. 1a) is the continuing interference registration. The drawback is the demand on receiver dynamic range.

The effect on the integrated side-lobe level of blocking data frequency bands stands in proportion to the fraction of data, which are missing. Hence interference Doppler filtering will reduce side lobe level to the extent that the interference is compressed in the Doppler spectra. Assuming for instance that interference can be compressed to just 1 Hz, and since Doppler bandwidths are in the order of 100 Hz for VHF radar, a reduction of the order 20 dB is possible. For interference compression to 10 Hz the side-lobes caused by interference is reduced by 10 dB.

The major drawback of interference Doppler filtering is that its dynamic range is restricted by the fact that the Fourier transform will be based on relatively few samples

given that sampling occur at the radar PRF rate and that integration time is limited by interference de-correlation time. Hence 2-dimensional filtering is always applicable but does not generally meet the requirement of reducing the interference level to that of external random noise.

Interference Cancellation

Interference cancellation requires prediction of the interference for each particular reception interval of mixed interference and radar ground response. This prediction is then coherently subtracted from the incoming signal.

The major drawback of interference cancellation is that it is not inherently robust. Depending on the nature of the message to be cancelled, prediction can be more or less efficient. When the predicted signal is non-coherent to the interference, the attempt to perform interference subtraction will partially or totally fail and may even lead to an increased interference level!

Combined Cancellation and Filtering

Use of the two methods combined in series has the advantage of providing both the robustness of the 2-dimensional filtering and providing an enhanced dynamic range in the general case that the cancellation do work.

Measuring interference

There are two ways of measuring the interference signal, depicted in figures 1a and 1b. According to figure 1a the interfering signal is registered in intervals of time when radar transmission is held back and the received signal is not mixed with the radar ground response. From these pure interference registrations the interfering component is predicted and applied at later times to transmit signal and to pulse compression on the mixed signal of interference and ground response.

Alternatively, the coherency of the interference may be used to separate it from the radar ground response, in which case the interference signal can be registered essentially continuously (cf. Figure 1b). In this scheme, in the demodulation of the interference, the radar response will appear as additional noise, which will be weak compared to the inter-

ference. It would thus not upset the interference demodulation scheme or the derived phase estimate.

Note that in Figure 1b, the radar response Doppler components, which have a sufficiently slow de-correlation to pass the LP filters of Figure 2, will be subtracted from the mixed signal along with interference. As these are restricted to the Doppler band anyway infested by interference this will do no extra harm in the interference filtering process. According to Figure 1a, cancellation may be used to reduce the requirement on receiver linearity. However, granted the availability of a sufficiently linear receiver, it will be possible to implement in the subsequent signal processing of the received signals, thus allowing for a continuing interference registration.

Prediction filter

Humans have a limited capacity for storing new information, and so the information bandwidth of radio and television signals will be small, and the degree of correlation very high in comparison with the signal bandwidth. In mathematical terms, one would say that there is a time T, much larger than the reciprocal of the bandwidth, such that the power of the transmitted message – be it video (moving imagery) or audio (sound) – is small outside a 1/T low pass filter, through which the message passes. The time T, which is different for video and audio, is the prediction length. The low pass filter is 2-dimensional for video and 1-dimensional for audio. We will discuss both the video and audio cases in the sequel.

Figure 2 depicts a filter for interference prediction. The filter comprises an interference data unit 20, a frequency allocation register containing a list of communication channels (e.g. broadcast channels) in the band used for radar operation, which may be prevalent in the given area of operation, a modulation standards register 21 containing a list of modulation types for the listed communication channels, an image prolongation unit 24, an audio prolongation unit 25, a motion estimation unit 23, a (sub-)carrier phase prediction unit (compensating platform motion) 26; an upconverter unit 28, a video low pass filter 27 (say 1 Hz), an audio low pass filter 29 (say 10 Hz).

The interference prediction is based on demodulation of known interference sources, e.g. TV-channels. The information content is identified and based on its character – images or audio – methods discussed below are utilised to estimate the signal amplitude at

some later time. Estimates are low pass filtered according to a characteristic rate of development depending on the type of message. Separate low pass filters for video and audio are provided. The estimated signal is finally unconverted by the carrier frequency.

Prediction of audio

Music is probably the most ordered form of human communication, being based on the harmonics and sub-harmonics of the musical scale. Most of the energy content of music is therefore made up of discrete set sinusoids ringing at least for the period of the musical beat.

A feel for the musical phase stability can be obtained considering that the instruments are tuned to each other by listening to the beat frequency between them. This will make the tuning quite accurate and musical tone highly stable for fractions of a second at least.

Speech is less coherent than music but also depending on fewer parameters at any moment of time. Speech is dominated by the pronunciation of vowels, made up by harmonics – formants - starting from a fairly low fundamental tone (say 200 Hz) setting the pitch of the voice. The human vocal cord and tract act as the resonating strings or membranes in musical instruments. Vibrating, it will produce a certain characteristic relation between the intensities of the formants, making up the sound of a vowel. By the dynamics of vocal cord and tract the different vowels are formed. The sound signal will remain well correlated for the duration of the vowels. But even for longer times the sound pattern may stay reasonably well correlated since voice pitch will vary at a slower rate than the rate at which vowels are spoken. Typically this rate is of the order of 10 Hz or so. It follows that only a marginal fraction of sound energy (-20 dB) de-correlates faster than - say - 0.2 s.

The conclusion is thus that voice communication is strongly coherent for some fraction of a second – be it music or speech.

Prediction of the sound requires determination of the frequency and the amplitude of the harmonics. The common principle applicable for both music and speech is to adopt a somewhat long integration time (say 0.2 – 1 s) to accurately establish the exact fre-

quency of the fundamental tone of the sound signals and then adopt a much shorter time (say 0.02 s - 0.05 s) to establish the magnitude of the harmonics and sub-harmonics of the fundamental tone. Thus it will be possible to coherently predict the sound signals for the period of the vowel or the beat

Prediction of Video

The term "visual persistence" refers to the fact that the human mind will not recognise the abrupt difference between still images, if they are similar enough and the frame rate of their individual exposure is high enough. This is the basic physiologic / psychological mechanism behind cinematography and video.

As is well known, frame rate for video and cinematography is 25 or 30 Hz. At lower rates - 12 – 16 Hz - frame shift flicker is noticeable. The flicker should however not be confused with the speed the human mind memorises and interprets an image. To memorise one single still image, it must probably be exhibited for 100 ms or more. To interpret this short impression takes much longer - several seconds. For a series of several consecutive but independent images to be interpretable, the rate at which they appear must be correspondingly slow. For this reason moving imagery shown as television or cinematography is fairly stationary or it would be quite senseless to watch it for any length of time. It is a fair guess that as mean value over extended periods of time, de-correlation times of 1 s can be expected. De-correlation for video thus occurs significantly slower than for audio. This could be understood in that the information content in a single beat of music or the pronunciation of vowel is so much smaller that that of an image, that the rate at which independent sounds can received by the human mind can be so much faster. While correlation lengths and thus predictability for 1 s are expected, the difficulty to utilise this length time may vary.

While traditional ways of producing moving imagery rely on a camera, which is still for most parts of the time, modem filmmakers let the camera move to a significant extent. Experiencing the latter type of imagery, the human mind compensates for the shifts on the screen and thus makes the correlation. Such more advanced ways of correlation can also be performed automatically by the system, as is already done in advanced video encoders ("motion compensation").

For television, apart from the discussed screen-to-screen quasi-periodicity, the transmitted signal builds line scans on the screen. For the different TV systems – PAL, NTSC, and SECAM, the screen rate is about 25 Hz. Prediction is based on at least one screen period of continuous collection of the interference signal. In the proposed prediction scheme, collection is interrupted by radar transmission periods, which means that collection must extend over several screen periods. Also prediction compensating for screen translation will require more extended periods for the prediction of the video signal. The different TV systems are distinguished by e.g. the different ways they code colour into the TV signals and how they adjust colour phase errors, which are clearly important aspects also in the coherent prediction of TV signals. The details of the different systems for coding/encoding are well known and can be incorporated in the required demodulation prediction and modulation chain.

Apart from analogue transmission one may encounter digital modulation systems. In e.g. OFDM – orthogonal frequency division multiplexing - the TV signal is de-multiplexed into – for VHF – 6000 channels, each holding a 64 place complex amplitude for 1 ms. The amplitudes are read off and put into an IFFT turning them into a time message of 6 MHz bandwidth and 1 ms duration at any suitable carrier frequency. Clearly there is no difference in principle between this modulation and analogue modulation as regards the possibility of interference prediction, but possibly for the fact that for OFDM the exact key to the modulation must be at hand and cannot be "guessed".

Claims

1. Radar system according to any part of the description.

Abstract

A filter scheme for broadcast interference cancellation that is computationally efficient and numerically robust Airborne Low Frequency Synthetic Aperture Radar (SAR) operating in the VHF and UHF bands has been shown. At least interference Doppler filtering or interference cancellation is utilised. The interference cancellation involves prediction of the interference for each particular reception interval of mixed interference and radar ground response. This prediction is then coherently subtracted from the incoming signal.

fig. 1a

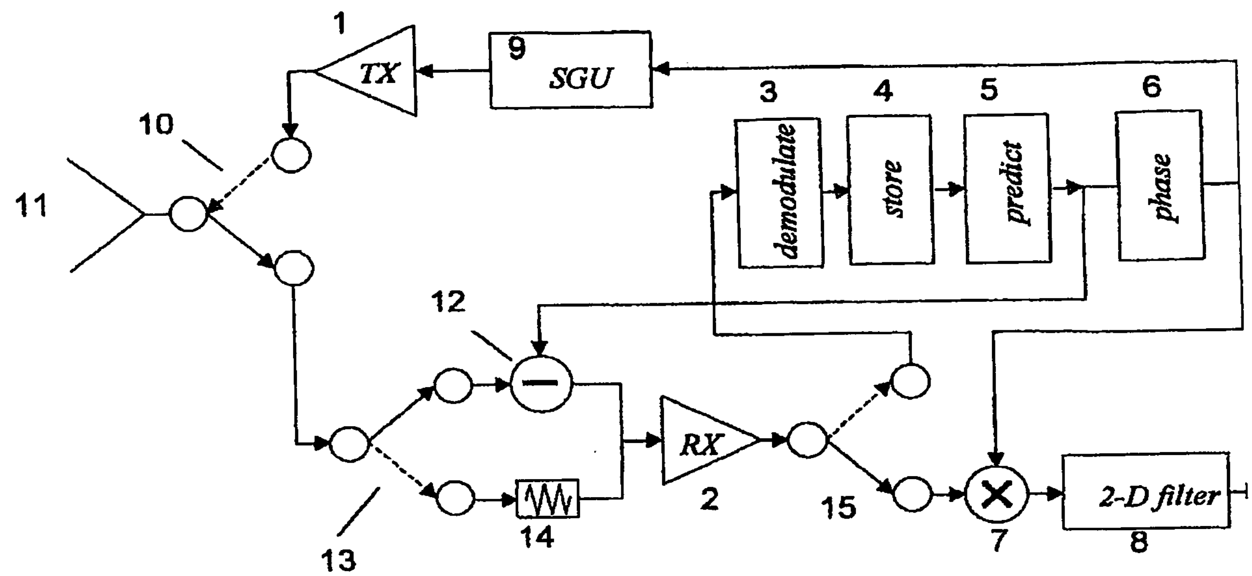
1
TX
9
SGU
3
demodulate
4
store
5
predict
6
phase
10
11
12
RX
2
15
2-D filter
7
8
14
13

Fig. 1a

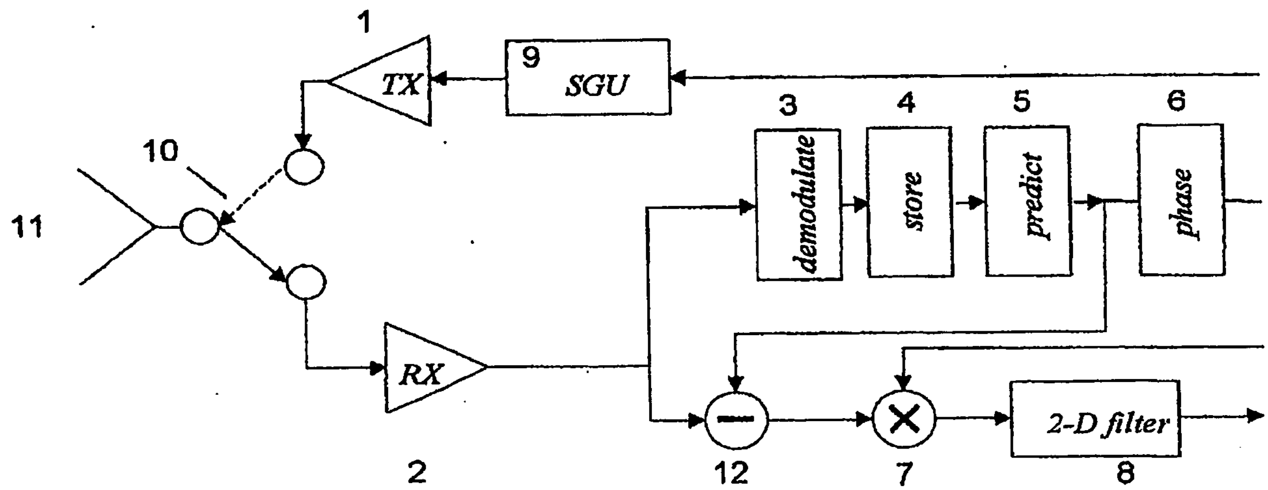
1
TX
9
SGU
3
demodulate
4
store
5
predict
6
phase
10
11
RX
2
12
7
2-D filter
8

Fig. 1b

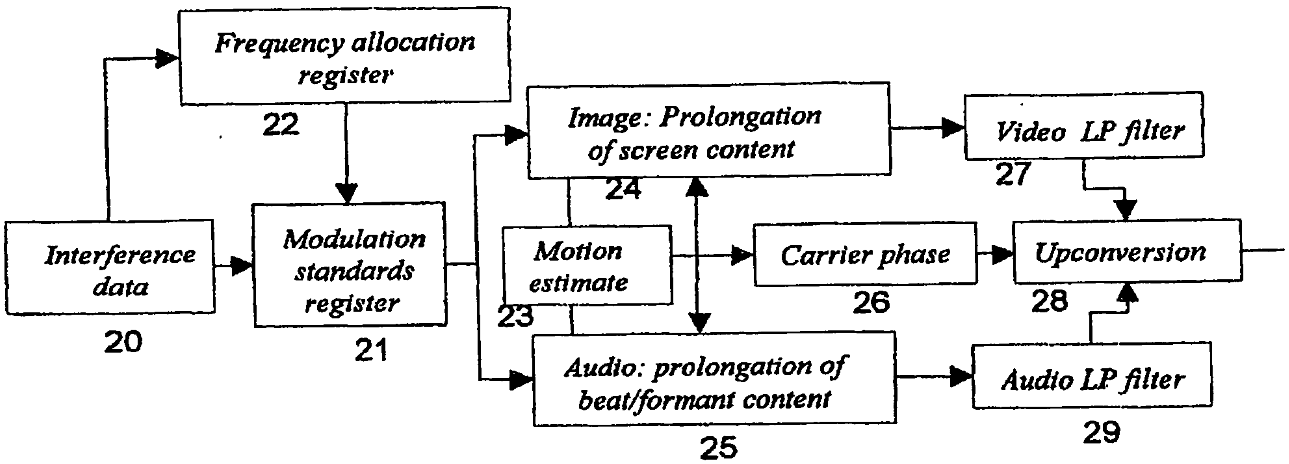
Frequency allocation register
22
Image: Prolongation of screen content
24
Video LP filter
27
Interference data
20
Modulation standards register
21
Motion estimate
23
Carrier phase
26
Upconversion
28
Audio: prolongation of beat/formant content
25
Audio LP filter
29

Fig. 2